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NON-PROVISIONAL APPLICATION
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FOR

A 4H-POLYTYPE GALLIUM NITRIDE-BASED SEMICONDUCTOR DEVICE ON a 4H-POLYTYPE SUBSTRATE

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FIELD OF THE INVENTION

The present invention relates to semiconductor devices using 4H-polytype GaN-based nitride semiconductor epitaxial layers grown on 4H-polytype substrates, and more particularly relates to method for increasing emission efficiency of the GaN-based optoelectronic devices and enabling high speed and high power operations of the GaN-based electronic devices.

BACKGROUND

III-V nitrides are wide band gap III-V compound semiconductors which contain nitrogen as a group-V element, and generally written as $B_{1-x-y-z}In_xAl_yGa_zN$ ($0 \leq x \leq 1$, $0 \leq y \leq 1$, $0 \leq z \leq 1$). Such III-V nitrides are widely used for visible light emitting diodes (LEDs) in many applications such as various indicators, traffic signals and so on. In addition, excitation of fluorescent material using the GaN-based blue or ultraviolet LEDs enables emitting white light, which would replace current light bulbs with longer lifetime. A blue-violet GaN-based semiconductor lasers for high-density optical disk systems is also a promising application of III-V nitrides. At present, III-V nitride lasers are commercially available for proto-type high density optical disk systems. High speed and high power GaN-based transistors are potential applications as well.

Due to the difficulties to obtain lattice-matched III-V nitride substrates, conventional III-V nitride devices are grown on foreign substrates such as sapphire or SiC. Among such foreign substrates,SiC is very promising since it has closer lattice constant from that of III-V nitrides as well as better thermal conductivity. SiC is also well-known material which has polytypism such as 3C-, 4H-, 6H-, 15R-type. So far, epitaxial growth of III-V nitrides on the various SiC polytypes are disclosed.

Karino et al. (Japanese Patent Published H8-125275) disclosed hexagonal III-V nitride-based laser devices on 2H-, 4H- and 6H-polytypes of (11-20) a-face or (10-10) m-face SiC substrates.

Hatano et al. (USP5,432,808) disclosed formation of InGaAlN-based device on 3C (cubic) SiC (111) substrate.

Stummer et al. (Physical Review Letters Vol.77, No.9, (1996) p.1797-1799) explained the epitaxial growth of 2H-AlN on 6H-SiC substrate.

However, how the combination of the polytype of SiC substrate and that of the overgrown III-V nitrides affect the crystal quality is not still clear. This invention is disclosed based on experimental results by inventors of this disclosure to find the best combination of the polytypes in view of crystal quality.

SUMMARY OF THE INVENTION

Accordingly, it is an object of present invention to provide the best combination of the polytypes for both SiC substrate and the overgrown III-V nitrides. The present invention provides a structure and method for overcoming many of the aforesaid limitations of the prior art by choosing the best combination of the polytypes, as summarized below and described in greater detail hereinafter.

The present invention provides a semiconductor device comprising a 4H-type epitaxial III-V nitride film grown on a 4H-type substrate. The substrate material is preferably SiC, and/or preferably (11-20) a-face. The III-V nitride epitaxial film preferably comprises AlN. The number of the group III atoms on the surface of the III-V nitride film is preferably equal to the number of nitrogen atoms on the surface.

In a somewhat different application, the present invention also provides a semiconductor laser comprising a 4H-type epitaxial III-V nitride film grown on a 4H-type substrate. The substrate material is preferably SiC, and/or preferably (11-20) a-face. The III-V nitride epitaxial film preferably comprises AlN. The number of the group III atoms on the surface of the III-V nitride film is preferably equal to the number of nitrogen atoms on the surface. It is also preferred that the waveguide is formed as a straight line perpendicular to either (0001) face or (1-100) face. The III-V nitride preferably contains either 4H-AlN or conductive 4H-AlGaN as a initial layer of the epitaxial growth. Highly conductive p-type 4H-SiC is preferably used with p-type 4H-AlGaN initial layer. The semiconductor laser may contain laterally epitaxial grown layers with reduced dislocation density on which the waveguide is formed. The seed layer of the lateral epitaxial growth is preferably 4H-GaN on 4H-AlN. It is also preferred that the lateral growth starts from the 4H-GaN and preferably air gaps are formed between the SiC substrate and the laterally grown layer. The semiconductor laser is preferably cleaved along to either <0001> or <1-100> direction.

In a somewhat different application, the present invention also provides a light emitting diode(LED) comprising a 4H-type epitaxial III-V nitride film grown on a 4H-type substrate. The substrate material is preferably SiC, and/or preferably (11-20) a-face. The III-V nitride epitaxial film preferably comprises AlN. The number of the group III atoms on the surface of the III-V nitride film is preferably equal to the number of nitrogen atoms on the surface. It is also preferred that the SiC substrate is p-type and the top layer of the III-V nitride layer is n-type on which ohmic contact is formed without any transparent electrode.

In a somewhat different application, the present invention also provides a transistor comprising a 4H-type epitaxial III-V nitride film grown on a 4H-type substrate. The substrate material is preferably SiC, and/or preferably (11-20) a-face. The III-V nitride epitaxial film preferably comprises AlN. The number of the group III atoms on the surface of the III-V nitride film is preferably equal to the number of nitrogen atoms on the surface. It is also preferred that the III-V nitride film comprises AlGaN on GaN or AlGaN on InGaN on GaN heterostructure. The III-V nitride film preferably comprises modulation-doped layers.

In a somewhat different application, the present invention also provides fabrication methods of semiconductor laser, light emitting diode, and transistor comprising a 4H-type epitaxial III-V nitride film grown on a 4H-type substrate. The substrate material is preferably SiC, and/or preferably (11-20) a-face. The III-V nitride epitaxial film preferably comprises AlN. The number of the group III atoms on the surface of the III-V nitride film is preferably equal to the number of nitrogen atoms on the surface. The fabrication method of a semiconductor laser may contain lateral epitaxial growth and preferably the seed layer of the lateral growth may be selectively etched 4H-GaN on 4H-AlN. It is also preferred that the lateral growth starts from the 4H-GaN so that air gaps are formed between the SiC substrate and the laterally grown layer.

These and other objects, advantages and features of the invention will be set forth in part in the description which follows and in part will become apparent to those having ordinary skill in the art upon examination of the following, or may be learned from the practice of the invention. The advantages of the invention may be realized and attained as particularly pointed out in the attained claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a cross sectional view of a III-V nitride-based blue-violet seemiconductor laser with 4H-polytype on 4H-AlN/4H-SiC as one embodiment of the present invention.

Figure 2 is an illustration of atomic configuration on 4H-SiC (11-20) a-face.

Figure 3 is an illustration of atomic configuration on 6H-SiC (11-20) a-face.

Figure 4 is an illustration of atomic configuration on 2H-AlN (11-20) a-face as is also seen in all of the III-V nitride with 2H-polytype.

Figure 5 is an illustration of band diagram of InGaN/GaN quantum well with 2H-polytype on a polar c-face substrate.

Figure 6 is an illustration of band diagram of InGaN/GaN quantum well with 4H-polytype on a non-polar a-face substrate.

Figure 7 is an illustration of atomic arrangement of AlN on SiC substrate both on polar and non-polar faces.

Figure 8 is processing flow of epitaxial growth of III-V nitride layers with initial AlN buffer layer on a 4H-SiC(11-20) substrate.

Figure 9 is reflection high-energy electron diffraction (RHEED) patterns of AlN layer on a 4H-SiC(11-20) substrate and on a 6H-SiC(11-20) substrate.

Figure 10 is lattice images of AlN on 4H-SiC(11-20) and AlN on 6H-SiC(11-20) measured by high resolution transmission electron microscope (HRTEM).

Figure 11 is x-ray rocking curve profiles on (11-20) diffraction for AlN on 4H-SiC(11-20) and on 6H-SiC(11-20).

Figure 12 is a cross sectional illustration of a III-V nitride-based blue-violet seemiconductor laser with 4H-polytype on 4H-AlN/4H-SiC in which the laser structure is formed epitaxial regrowth from narrow striped GaN/AlN seed layer as one embodiment of the present invention.

Figure 13 is a cross sectional illustration of a III-V nitride-based blue-violet seemiconductor laser with 4H-polytype on conductive 4H-AlN/4H-SiC in which the electrodes are formed on the both sides as one embodiment of the present invention..

Figure 14 is a cross sectional illustration of a III-V nitride-based ultravioler LED with 4H-polytype on conductive 4H-AlN/4H- SiC in which the electrodes are formed on the both sides as one embodiment of the present invention.

Figure 15 is a cross sectional illustration of a III-V nitride-based heterostructure transistor with 4H-polytype on 4H-AlN/4H- SiC as one embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

First Embodiment

(Device structure)

Referring first to Figure 1, one embodiment of the semiconductor laser of the present invention may be understood in greater detail. In particular, Figure 1 schematically illustrates a cross sectional view of a blue-violet semiconductor laser in which GaN-based epitaxial structure with 4H polytype is grown on (11-20) a-face of 4H-SiC substrate. The GaN-based epitaxial structure typically consists of p-type $Al_{0.07}Ga_{0.93}N$ cladding layer **106**, undoped InGaN multi quantum well active layer **105**, n-type $Al_{0.07}Ga_{0.93}N$ cladding layer **104** and n-type GaN base layer **103** .And the undoped InGaN multi quantum well active layer **105** is disposed between the p-type AlGaN cladding layer **106** and n-type AlGaN cladding layer **104** ,and these three layers are formed on the n-type GaN base layer **103** as shown in Figure 1. Moreover, n-type GaN base layer **103 is formed on the undoped AlN initial layer 102.** All of the epitaxial layers have 4H poly type and the layers are grown replicating the poly type of the 4H-SiC substrate **101**. In this embodiment, the word, GaN-based epitaxial structure has the structure including an epitaxial layer of which composition includes Ga and N. In this structure, cladding layer 104, active layer 105, and cladding layer 106 has the composition of Ga and N.

Detailed structural parameters of the semiconductor laser are summarized in Table 1. Table 1 shows the example for the thickness of each layer and the carrier concentrations of some layers including Ga and N. In Table 1, the carrier concentrations of p-AlGaN cladding layer and n-AlGaN cladding layer are substantially same, and the carrier concentration of the cladding layer is higher than the base layer. The active layer105 has the quantum well and barrier layer. As shown in table 1, the composition of the well layer is undoped In0.1Ga0.9N, and the composition of the barrier layer is undoped In0.02Ga0.98N. The thickness of the well layer and the barrier layer is 4nm. And the number of the well layer in the active layer 105 is three.

The (11-20) face represents the stacking sequence of the consisting atomic pair as shown in Figure 2. The atomic configuration on (11-20) shows the ABCB ABCB... sequence and the GaN-based epitaxial layer inherits the sequence without forming any dislocations by choosing appropriate growth conditions. Replacing the Si and C atoms to Al and N atoms respectively in Figure 2 represents the atomic configuration of the overgrown 4H-AlN layer.

On the other hand, in case the used substrate is 6H-SiC (11-20) face, of which the atomic configuration is shown in Figure 3. The atomic configuration on (11-20) shows the ABCACB ABCACB... sequence and the grown III-V nitride on the 6H face exhibits thermally stable 2H-polytype.

Figure 4 shows the atomic configuration of the overgrown 2H-AlN on (11-20) a-face and the atomic configuration on (11-20) shows the AB AB AB... sequence. As is easily expected from Figure 5 and Figure 6, the overgrown 2H-configuration contains a lot of faulted region due to the disarrangement of the atoms at the interface.

In contrast the 4H-AlN on 4H-SiC (11-20) heterostructure does not contain such disarrangement as is described below in detail. The (11-20) is so-called non polar face on which both group III and nitrogen atoms are located. On the other hand, commonly used (0001) c-face of the III-V nitride device layer is polar face on which either group III or nitrogen atoms are located. Since polarization is aligned along (0001) direction of III-V nitride epitaxial films, the build in electric fields are produced by the spontaneous and piezoelectric polarization on such polar face. The electric field in the quantum well structure results in lower light emission efficiency with the longer wavelength, which is so-called quantum confined Stark effect. Even undoped AlGaN/GaN hetero structure exhibits sheet carrier concentration in the order of 10^{13}cm^{-2} as well. Figure 5 shows the band diagram of the quantum wells on the polar face. This quantum well structure is composed of the 2H-InGaN well layer and 2H-GaN barrier layer. This figure shows the wave functions both of electrons and holes in the quantum well. The band is distorted due to the electric field mainly by the piezoelectric polarization. The electrons and holes are spatially separated in the well so that the emission efficiency is reduced. That is, it needs much larger electron energy to maintain high emission efficiency because of the separation of the electrons and holes shown in Fig5. In addition, the emission wavelength is longer than that without any electric field.

On the contrary, the double hetero epi-structure with 4H-polytypes with non polar a-face described in the first embodiment exhibits a band structure as shown in Figure 6. In this figure 6, this quantum well structure is composed of the 2H-InGaN well layer and 2H-GaN barrier layer. Since the a-face is a non-polar face, any polarization-induced electric field is not seen perpendicular to the quantum well in the band diagram. Thus, emission efficiency from the quantum well is increased from that on the polar c-face with such electric field due to the polarization. Note that the wavelength of the emitted light is shorter than that on the polar face.

Figure 7 schematically summarizes the atomic arrangement both on the non-polar and polar faces with the direction of the produced polarization. In Figure 7(a) the boundary surface between AlN layer and SiC substrate has a mixed crystal structure comprising Al, N, Si, C so that these atomic polarizations are neglected each other. However, in figure 7 (b) the boundary surface between AlN layer and SiC substrate comprises single crystal multi layers deposited each other so that atomic polarization is generated especially on the boundary surface as indication by an arrow.

(Fabrication process)

Referring next to Figure 8, the detailed structure and the process sequences of the semiconductor laser as the first embodiment are described as follows.

First, 380nm-thick 4H-AlN is grown on a surface of a 4H-SiC (11-20) substrate **301** by molecular beam epitaxy (MBE).

In a degreasing step the 4H-SiC (11-20) substrate **301** is first degreased using organic solvents.

In a wet chemical treatment step the 4H-SiC (11-20) substrate **301** is dipped in solutions in turn. First solution is HCl, second solution is HCl + HNO3 (3:1) and third solution HF.

In a thermal cleaning step the 4H-SiC (11-20) substrate **301** is thermally cleaned at 1000℃ for 30 minutes to make a flat and/or a clean surface of the substrate 301, and then loaded into the MBE chamber.

Then, in a growth of an AlN buffer layer step the AlN layer **302** is epitaxially grown by supplying metal Al source from an effusion cell and the radical nitrogen atoms from RF plasma source. Typical growth temperature for the AlN layer is 1000°C with an Al beam equivalent pressure of 4.7×10^{-7} Torr and RF power of 400W with a nitrogen flow rate of 0.5sccm. The growth rate under the condition is 380nm/hr.

After the MBE growth, in a growth of Ⅲ-V nitride epitaxially layers step the wafer is reloaded to a metal organic chemical vapor deposition (MOCVD) reactor to grow GaN-based double hetero structure for the blue-violet laser. Trimethyl gallium (TMGa) and ammonia are supplied for the GaN growth.

Trimethyl aluminum (TMAl) and/or trimethyl indium (TMIn) are added for the ternary or quaternary alloy growth. Cp_2Mg and SiH_4 are used for the p-type and n-type doping, respectively. As shown in Figure1, 4μm-thick n-GaN is grown on the MBE-grown 4H-AlN layer **102**. The GaN layer exhibits 4H-polytype on (11-20) face. Subsequently, 1μm-thick n-$Al_{0.07}Ga_{0.93}N$ cladding layer **104**, undoped InGaN multi-quantum well active layers **105**, 0.5μm-thick p-$Al_{0.07}Ga_{0.93}N$ cladding layer **106** is grown on the n-GaN layer **103**. Both n-GaN layer and p-GaN layer guiding layer typically with the thickness of 100nm may be attached on and underneath the active layers **105**. P-AlGaN with higher Al content may be placed between the p-type cladding layer **106** and the active layer **105** to suppress the overflow of the electrons. P-GaN with high Mg concentration may be grown on the top of the p-$Al_{0.07}Ga_{0.93}N$ cladding layer **106**. All of the regrowth layer by MOCVD exhibit 4H-polytype inheriting the atomic sequence of 4H-AlN layer. Thus obtained non-polar active layer does not affected by the built-in electric field due to the piezoelectric polarization so that higher emission efficiency with shorter wavelength is possible.

Dry etching process such as inductive coupled plasma (ICP) etching using Cl_2 selectively etches the p-type AlGaN cladding layer **106** to form the straight ridge-shaped waveguide using a patterned photo resist as a mask. Then, the same etching technique etches the active layer 105 and cladding layer **104** to expose the n-GaN layer **103** prior to the ohmic contact **109** formations on it.

After the two processing steps of the dry etching, a 300nm-thick SiO_2 film **110** is deposited, typically by using plasma assisted chemical vapor deposition. The SiO_2 film **110** on the side wall of the ridge-shaped waveguide confines the emitted light inside the ridge structure due to the difference of the effective refractive index between the SiO_2 **110** and the cladding layer **106**. Ni/Au layer(electrode) **108** as a ohmic contact on p-AlGaN cladding layer **106** and Ti/Al layer(electrode) **109** as a ohmic contact on n-GaN **103** are formed after the selective wet chemical etching of SiO_2 film **110** where the ohmic contacts are to be formed. The processed substrate is thinned from the back side typically down to 150 μ m. The cleaved facets are formed along to <0001> axis to form mirrors of the laser. Typical cavity length is 600 μ m. The fabricated laser exhibits lower threshold current density because of high emission efficiency on the non-polar face.

(Characterization of initial AlN epitaxial layer)

The AlN initial epitaxial layer is characterized in detail as is described below.

Figure 9 shows the reflection high energy electron diffraction (RHEED) pattern of the AlN layer on 4H-SiC and 6H-SiC. The pattern of AlN on 4H-SiC well corresponds with that of 4H-polytype, whereas the pattern of AlN on 6H-SiC indicates 2H-polytype. The polytype is replicated in AlN epitaxial layer from 4H-SiC substrate.

Figure 10 shows the microscopic structure of the AlN/4H-SiC (11-20) substrate and AlN/6H-SiC (11-20) substrate investigated by high-resolution transmission electron microscope (HRTEM). In order to clarify the stacking sequence in the AlN layer, a TEM sample is cut from the wafer with a 30° inclination as shown in Figure 10. As is seen in the 4H-SiC substrate region, one set of dark and bright bands corresponds to one unit cell of the 4H structure. The AlN epitaxial layer has just the same dark bright bands, indicating successful polytypic replication from the 4H-SiC substrate. The AlN epitaxial layer is the 4H polytype structure. On the contrary, as shown in Figure 9, AlN epitaxial layer on 6H-SiC (11-20) exhibits 2H-polytype.

Figure 11 shows the x-ray rocking curves (XRC) of (11-20) diffraction for 380nm-thick AlN epitaxial layers on 4H-SiC (11-20) substrate and 6H-SiC (11-20) substrate. Two different x-ray incident geometries parallel and perpendicular to the <1-100> direction are examined. The full width at half maximum (FWHM) exhibited a very small value of 90 arcsec, suggesting noticeably small tilting around the <11-20> direction. On the contrary, AlN layer on 6H-SiC substrate exhibited a large FWHM of 240 arcsec with the x-ray incident parallel to <1-100> as well as the peak is very weak. Thus, the crystal quality of the AlN epitaxial layer on 4H-SiC(11-20) substrate is much superior to that grown on the 6H-SiC(11-20) substrate. The poor crystal quality of the AlN on 6H-SiC substrate is probably attributed to many stacking faults or line defects, which is originated from polytype mismatch of 2H-AlN on 6H-SiC.substrate. The poor crystal quality would lead to higher operating current of the laser with shorter life time due to the non irradiative recombination centers caused by the crystal defects. The defect degrades the performances of the other kinds of devices as well.

The above-mentioned results shown in Figure 9-11 are summarized in Table 2.Table 2 describe the difference between the present invention and the compared example. The present invention has a 4H-a-face of AlN layer formed on a 4H-SiC substrate and the compared example has a 2H-a- face AlN layer formed on a 6H-SiC substrate. As shown in this table2, The combination of the overgrown layer with the 4H face and the substrate with 4H face is better than the combination of the overgrown layer with 2H face and the substrate with 6H face on these points such as "poly-type matching, crystal quality, and device performance". In this table, poly-type matching means the same indication of the poly-type between substrate and overgrown layer.

Second Embodiment

Referring next to Figure 12, there is schematic illustration of a non-polar GaN based blue-violet semiconductor laser on a 4H-SiC (11-20) a-face substrate **1201**. Basic epitaxial structures on 4H-SiC (11-20) a-face is identical with the structure as shown in Figure 1. However, dislocation density in the active layer underneath the waveguide 1208 is further reduced by employing the epitaxial lateral over growth technique. The resultant laser exhibits longer lifetime than that without any lateral growth region owing to the reduction of the dislocations. The emission efficiency from the quantum well in the laser is increased from that on the polar c-face with built-in electric field due to the polarization, which leads to lower threshold current density.

As shown in Figure 12, the epitaxial structure of the laser typically consists of an undoped InGaN multi quantum well active layer **1206** formed between a p-type $Al_{0.07}Ga_{0.93}N$ cladding layer **1207** and an n-type $Al_{0.07}Ga_{0.93}N$ cladding layer **1205** and n-type GaN base layer **1204** formed under the n-type $Al_{0.07}Ga_{0.93}N$ cladding layer **1205**. Under the n-GaN base layer 1204, 380nm-thick AlN initial layer **1202** is formed selectively in the shape of narrow stripe. The stripe is formed in the surface of the 4H-SiC substrate 1201. The stripe width is typically 5μm and the distance of each stripe is 15μm. Dislocation density at the active layer **1206** underneath the waveguide 1208 is at around $1 \times 10^6 cm^{-2}$ or less, because the lateral growth reduces the dislocation density. The direction of the stripe is preferably <1-100> direction, which is perpendicular to the stacking direction. Resultant lateral growth to <1-100> keeps the poly type in the wing region **1212** from that in the seed region**1203**.

On the contrary, if the direction of the stripe is <0001> direction, the stacking order of the atoms in the wing region **1212** is determined by the growth condition rather than the stacking order in the wing region **1212**. The detailed structural parameters of the semiconductor laser are summarized in Table 3. Table 3 discloses the thickness and carrier concentration each layers in one example. In Table.3 a p-type AlGaN cladding layer has substantially same carrier concentration "5×10^{17} cm^{-3}" as an n-type AlGaN cladding layer, and an n-type GaN base layer has substantially same carrier concentration "1×10^{18} cm^{-3}" as an n-type GaN seed layer. And an undoped AlN layer 1202 and an undoped quantum wells 1206 is not doped. The active layer1206 has the quantum well and barrier layer. As shown in table 2, the composition of the well layer is undoped In0.1Ga0.9N, and the composition of the barrier layer is undoped In0.02Ga0.98N. The thickness of the well layer and the barrier layer is 4nm. And the number of the well layer in the active layer 105 is three.

The detailed processing procedures are as follows. First, 380nm-thick 4H-AlN is grown on 4H-SiC(11-20) face by molecular beam epitaxy (MBE) .Details is described same as in the first embodiment as following.

In a degreasing step the 4H-SiC (11-20) substrate **1201** is first degreased using organic solvents.

In a wet chemical treatment step the 4H-SiC (11-20) substrate **1201** is dipped in solutions in turn. First solution is HCl, second solution is HCl + HNO3 (3:1) and third solution HF.

In a thermal cleaning step the 4H-SiC (11-20) substrate **1201** is thermally cleaned at 1000℃ for 30 min to make a flat and/or a clean surface of the substrate, and then loaded into the MBE chamber.

Then, in a growth of an AlN buffer layer step the AlN layer **1202** is epitaxially grown by supplying metal Al source from an effusion cell and the radical nitrogen atoms from RF plasma source. Typical growth temperature for the AlN layer is 1000°C with an Al beam equivalent pressure of 4.7×10^{-7} torr and RF power of 400W with a nitrogen flow rate of 0.5sccm. The growth rate under the condition is 380nm/hr.

After the MBE growth, n-type 4H-GaN seed layer **1203** having 2μm-thickness is grown on the 4H-AlN initial layer **1202** by MOCVD.

Then, the n-type 4H-GaN seed layer **1203** and the 4H-AlN initial layer **1202** are selectively etched by dry etching such as ICP etching. Stripe pattern along to <0001> direction with the width of typically 5μm is formed. Preferably, as shown in Figure 12, grooves in SiC between wing regions **1212** such as GaN/AlN stripes are formed subsequently by the same etching procedure.

After the stripe patterning, n-type 4H-GaN base layer having 4μm thicknesses is grown on the stripes by lateral epitaxial growth. The laterally growth reduced dislocation density from that at the stripe region of the n-type 4H-GaN seed layer **1203**. Note that the lateral growth takes place from the n-type 4H-GaN seed layer **1203** on the stripe of the 4H-AlN initial layer **1202**, so that the no epitaxial film is grown on the sidewall of the 4H-AlN initial layer **1202**. Subsequently, n-type 4H-$Al_{0.07}Ga_{0.93}N$ cladding layer **1205** having 1μmthickness, an undoped InGaN multi-quantum well active layers **1206**, p-type 4H-$Al_{0.07}Ga_{0.93}N$ cladding layer **1207** having 0.5μm-thickness are grown on the n-type 4H-GaN base layer **1204**. All of the epitaxial growth layers exhibit 4H-polytype inheriting the atomic sequence of 4H-AlN initial layer1202.

Following dry etching processes selectively etches the p-type 4H AlGaN cladding layer 1207 to form the straight ridge-shaped waveguide **1208** as well as the 4H-InGaN multi quantum well active layer **1206** and n-type 4H AlGaN cladding layer **1205** to expose the n-type 4H-GaN base layer **1204**.

After the etching steps, a 300nm-thick SiO_2 film **1211** is deposited to confine the emitted light in the waveguide **1208**. Ni/Au layer(electrode) **1209** as a p-ohmic contact and Ti/Al layer(electrode) **1210** as an n-ohmic contact are formed in contact with the SiO2 film **1209**. The substrate thinning process followed by the cleaving process is conducted to fabricate a blue-violet laser diodes on the non-polar face with lower threshold current density.

Third Embodiment

Referring next to Figure 13 (a) and (b), non-polar GaN-based blue-violet laser diodes on 4H-SiC (11-20) a-face substrates with two electrodes on the both sides of the laser chip are shown. Epitaxial structure on 4H-SiC (11-20) a-face is basically identical with the structure shown as the first embodiment except for the initial layer. In the first embodiment, the initial layer is AlN, however in this embodiment, the initial layer which is formed on the substrate 1301 is conductive AlGaN layer. And also in this embodiment, the 4H-SiC substrate 1301 is conductive to enable the vertical device configuration. The emission efficiency from the quantum well in the laser on the non polar face is increased from that on the polar c-face with built-in electric field due to the polarization, which leads to lower threshold current density together with low series resistance and operating voltage owing to its vertical device configuration.

As shown in Figure 13 (a) and (b), the epitaxial structure of the laser typically consists of p-type $Al_{0.07}Ga_{0.93}N$ cladding layer **1304**, undoped InGaN multi quantum well active layer **1303**, n-type $Al_{0.07}Ga_{0.93}N$ cladding layer **1302**.

The laser structure on n-type 4H-SiC **1301** as shown in Figure 13 (a) has an n-type 4H-AlGaN initial layer as a part of the n-type 4H-cladding AlGaN layer **1302**. In this device 4H-InGaN multi quantum well active layer **1303** is formed between n-type 4H-cladding AlGaN layer **1302** and p-type 4H-cladding AlGaN layer **1304**, and a waveguide of a semiconductor laser **1305** is formed on the p-type 4H-cladding AlGaN layer **1304**.

Additionally these GaN based epitaxial structure are formed between ohmic contacts. That is Ni/Au ohmic contact(electrode) **1306** is contacted with the waveguide and Ni ohmic contact(electrode) **1307** is formed underneath the n-type 4H-SiC (11-20) substrate **1301.** The Al composition in the n-type 4H-AlGaN cladding layer **1302** maybe varied to relax the lattice mismatch between the AlGaN (n-type 4H-AlGaN cladding layer **1302** or p-type 4H-AlGaN cladding layer **1304**) and the SiC substrate. The active layer1303 has the quantum well and barrier layer. As shown in table 4(a), the composition of the well layer is undoped In0.1Ga0.9N, and the composition of the barrier layer is undoped In0.02Ga0.98N. The thickness of the well layer and the barrier layer is 4nm. And the number of the well layer in the active layer 105 is three.

The laser structure on p-type 4H-SiC as shown in Figure 13 (b) has a p-type 4H-AlGaN initial layer as a part of the p-type 4H-AlGaN cladding layer **1304**. Since the available p-GaN has carrier concentration up to 1 x 10^{18}cm^{-3} resulting the minimum attained ohmic contact resistance of 1 x 10^{-3} Ωcm^2, conventional GaN based laser diodes with the ridge waveguides **1305** in the p-type layer exhibits high series resistance owing to its narrow striped p-ohmic contacts. By using highly conductive p-SiC **1309** substrate with the resistivity of 0.01Ωcm and large area backside contact, operation voltage is far reduced from that of conventional p-layer top laser diode.

All of the III-V nitride layers shown in Figure 13 (a) and (b) have 4H-polytype replicating that of the SiC substrate. The detailed structural parameters of the semiconductor lasers are summarized in Table 4. Table 4 discloses the thickness and carrier concentration each layers in one example. In Table 4 (a) an n-type AlGaN cladding layer has substantially same carrier concentration "1×10^{18} cm^{-3}" as an n-type AlGaN initial layer, and an p-type GaN cladding layer has higher carrier concentration "5×10^{17} cm^{-3}" than an n-type GaN cladding layer. And an undoped quantum wells have few or no carrie. In Table4 (b) a p-type AlGaN cladding layer has substantially same carrier concentration "1×10^{18} cm^{-3}" as a p-type AlGaN initial layer, and an n-type GaN cladding layer has higher carrier concentration "5×10^{17} cm^{-3}" than a p-type GaN cladding layer. And an undoped quantum wells have few or no carrie.

The detailed processing procedures are described for the embodiment on p-type SiC substrate 1309.

First, 380nm-thick p-type 4H-Al$_{0.5}$Ga$_{0.5}$N initial layer is grown on p-type 4H-SiC(11-20) face substrate 1301 by molecular beam epitaxy(MBE) using the same epitaxial procedure explained in the first embodiment.

In a degreasing step the p-type 4H-SiC (11-20) substrate **1309** is first degreased using organic solvents.

In a wet chemical treatment step the p-type 4H-SiC (11-20) substrate **1309** is dipped in solutions in turn. First solution is HCl, second solution is HCl + HNO3 (3:1) and third solution HF.

In a thermal cleaning step the p-type 4H-SiC (11-20) substrate **1309** is thermally cleaned at 1000℃ for 30 min to make a flat and/or clean surface of the substrate ,and then loaded into the MBE chamber.

The dopant Mg is introduced from the heated effusion cell in the MBE. Dopant atom is showing shallower acceptor level with low resistivity.

After the MBE growth, p-type 4H $Al_{0.07}Ga_{0.93}N$ cladding layer **1304** having 0.5μm-thickness, undoped InGaN multi-quantum well active layers **1303**, n-type 4H $Al_{0.07}Ga_{0.93}N$ cladding layer **1302** having 0.5μm-thickness are grown by MOCVD. As explained in the first embodiment, n-type 4H AlGaN cladding layer **1302** and p-type 4H AlGaN cladding layer **1304**, p-type 4H AlGaN with higher Al content maybe placed between the p-type 4H $Al_{0.07}Ga_{0.93}N$ cladding layer 1304 and the active layer **1303**. All of the regrowth layers exhibit 4H-polytype inheriting the atomic sequence of the MBE grown p-type 4H-AlGaN layer **1304**.

Following dry etching processes selectively etches the n-type 4H-AlGaN cladding layer 1302 to form the straight ridge-shaped waveguide **1305**.

After the etching steps, a SiO_2 film **1308** having 300nm-thickness is deposited to confine the emitted light in the waveguide **1305**. Then Ti/Au layer (electrode) **1310** as an n-ohmic contact **1310** is formed on the waveguide **1305**. Wafer thinning process and Al-Si ohmic contact (electrode) **1311** formation for p-type SiC substrate followed by the cleaving are conducted to fabricate a blue-violet laser diodes on the non-polar face with vertical device configuration. In case the laser is formed on n-type SiC substrate, the top p-type ohmic contact is Ni/Au **1306**, and back side contact for n-SiC is Ni **1307**.

Fourth Embodiment

Referring next to Figure 14 (a) and (b), non-polar GaN-based ultraviolet light emitting diode (LED) on 4H-SiC (11-20) a-face substrates with two electrodes on the both sides of the LED chip are shown. The initial layer is conductive AlGaN layer and the 4H-SiC substrate is also conductive to enable the vertical device configuration. The emission efficiency from the quantum well in the LED on the non polar face is increased from that on the polar c-face with built-in electric field due to the polarization, which leads to high luminous efficiency together with low series resistance and operating voltage owing to its vertical device configuration.

As shown in Figure 14 (a) and (b), the epitaxial structure of the ultraviolet LED typically consists of p-type 4H $Al_{0.25}Ga_{0.75}N$ cladding layer **1404**, undoped 4H InAlGaN multi quantum well active layer **1403**, n-type 4H $Al_{0.25}Ga_{0.75}N$ cladding layer **1402**.

The LED structure on n-type 4H-SiC **1401** as shown in Figure 13 (a) has an n-type 4H AlGaN initial layer as a part of the n-type 4H AlGaN cladding layer **1402**. The Al composition in the n-type 4H-AlGaN cladding layer **1402** maybe varied to relax the lattice mismatch between the n-type 4H-AlGaN 1402 and the n-type 4H SiC (11-20) substrate 1401.

The LED structure on p-type 4H-SiC **1409** as shown in Figure 13 (b) has a p-type 4H-AlGaN initial layer as a part of the p-type 4H-AlGaN cladding layer 1404. As explained in the third embodiment, available p-type GaN or p-type AlGaN has carrier concentration up to $1 \times 10^{18} cm^{-3}$ resulting the minimum attained ohmic contact resistance of $1 \times 10^{-3}\ \Omega cm^2$. In order to obtain enough current spreading in the p-type layer top LED configuration, conventional GaN based LED with the p-type top layer uses transparent electrode such as thin Ni/Au **1406** with a Au top electrode **1407** together with Ni ohmic contact **1408** for n-type 4H-SiC (11-20) substrate as shown in Figure 14 (a). The transparent electrode may absorb the emitted light so that the thickness needs to be precisely controlled to avoid the optical loss in the electrode. Thus in view of reproducible manufacturing, n-type layer top vertical device configuration is desired.

As shown in Figure 14 (b), the use of highly conductive p-SiC substrate with the resistivity of $0.01\Omega cm$ and elimination of the transparent electrode enable reduction of the operating voltage as well as high luminous efficiency. All of the III-V nitride layers shown in Figure 14 (a) and (b) have 4H-polytype replicating that of the 4H-SiC substrate. The detailed structural parameters of the LED are summarized in Table 5. In Table 5 discloses the thickness and carrier concentration each layers in one example.

Table 5 (a) shows a device having an n-type 4H-SiC (11-20) substrate. In Table 5 (a) an n-type AlGaN cladding layer has substantially same carrier concentration "5×10^{17} cm^{-3}" as a p-type AlGaN cladding layer, and an n-type AlGaN initial layer has substantially same carrier concentration "1×10^{18} cm^{-3}" as an n-type GaN contact layer and n-type AlGaN initial layer. And an undoped quantum wells are not doped. The active layer1403 has the quantum well and barrier layer. As shown in table 5(a), the composition of the well layer is undoped In0.02Al0.15Ga0.848N, and the composition of the barrier layer is undoped Al0.15Ga0.85N.

The thickness of the well layer is 2nm and the thickness of the barrier layer is 5nm. And the number of the well layer in the active layer 1403 is three.

Table 5 (b) shows a device having a p-type 4H-SiC (11-20)1409. In Table 5 (b) an n-type AlGaN cladding layer 1402 has substantially same carrier concentration "5×10^{17} cm^{-3}" as a p-type AlGaN cladding layer 1404, and an p-type GaN initial layer has lower carrier concentration "1×10^{18} cm^{-3}" than an p-type AlGaN cladding layer. And an undoped quantum wells 1403 are not doped.

The detailed processing procedures are described for the embodiment on p-type SiC (11-20) substrate 1409.

First, 380nm-thick p-type 4H-$Al_{0.5}Ga_{0.5}N$ is grown on p-type 4H-SiC (11-20) face by molecular beam epitaxy (MBE) as is explained in the third embodiment.

In a degreasing step the p-type 4H-SiC (11-20) substrate **1409** is first degreased using organic solvents.

In a wet chemical treatment step the p-type 4H-SiC (11-20) substrate **1409** is dipped in solutions in turn. First solution is HCl, second solution is HCl + HNO3 (3:1) and third solution HF.

In a thermal cleaning step the p-type 4H-SiC (11-20) substrate **1309** is thermally cleaned at 1000℃ for 30 min to make a flat and/or clean surface of the substrate, and then loaded into the MBE chamber.

The dopant Mg is introduced from the heated effusion cell in the MBE. Dopant atom is showing shallower acceptor level with low resistivity.

After the MBE growth, p-$Al_{0.25}Ga_{0.75}N$ cladding layer **1404** having 100nm-thickness, undoped InAlGaN multi-quantum well active layers **1403**, n-type $Al_{0.25}Ga_{0.75}N$ cladding layer **1402** having 100nm-thickness are grown by MOCVD. A p-type 4H-AlGaN with higher Al content than the cladding layer **1404** maybe placed between the p-cladding layer **1404** and the active layer to suppress the overflow of the electrons.

The multi quantum well **1403** may be InAlGaN(well layer)/AlGaN(barrier layer) quantum well to emit the ultraviolet light at around 340nm. All of the regrowth layers exhibit 4H-polytype inheriting the atomic sequence of the MBE grown 4H-AlGaN layer.

Then Ti/Au layer **1410** as a pad electrode is formed on the n-type 4H-AlGaN cladding layer **1402**. Wafer thinning and Al-Si ohmic contact **1411** formation for p-type SiC substrate are conducted to fabricate an ultra violet LED on the non-polar face with vertical device configuration.

Fifth Embodiment

Referring next to Figure 15, a non-polar III-V nitride-based transistor on non polar 4H-SiC (11-20) a–face is shown, in which electron mobility is enhanced in the AlGaN/GaN modulation-doped hetero structure. The epitaxial structure typically consists of n-type $Al_{0.25}Ga_{0.75}N$ layer **1505** formed on undoped 4H-AlN layer **1503**. Undoped 4H-$Al_{0.25}Ga_{0.75}N$ layer **1504** may be inserted between the n-type 4H-$Al_{0.25}Ga_{0.75}N$ layer1505 and the undoped 4H-AlN layer **1503**. The hetero structure is grown on a 4H-AlN initial layer **1502** as a buffer layer. All of the epitaxial layers have 4H-polytype and the layers are grown inheriting the polytype of the 4H-SiC substrate1501. The epitaxial layer does not contain any build-in electric field due to the polarization. Comparing conventional polar AlGaN/GaN hetero structure transistors, the non-polar device makes the device design easier in which the potential barrier caused by the built-in electric field does not have to be taken into account. The device is not affected by the internal electric field which might increase the series resistance of the device. In addition, non polar AlGaN/InGaN/GaN pseudomorphic modulation doped structure would result in enhanced electron mobility with high enough sheet carrier concentration.

The detailed structure and the process sequences are described as follows. First, 4H-AlN initial layer 1502 as a buffer layer is grown on a semi-insulating 4H-SiC (11-20) substrate **1501** having 380nm-thickness by molecular beam epitaxy (MBE) as is explained in the first embodiment.

In a degreasing step the p-type 4H-SiC (11-20) substrate **1501** is first degreased using organic solvents.

In a wet chemical treatment step the p-type 4H-SiC (11-20) substrate **1501** is dipped in solutions in turn. First solution is HCl, second solution is HCl + HNO3 (3:1) and third solution HF.

In a thermal cleaning step the p-type 4H-SiC (11-20) substrate **1501** is thermally cleaned at 1000℃ for 30 min to make a flat and/or clean surface of the substrate, and then loaded into the MBE chamber.

After the MBE growth, undoped 4H-AlGaN layer 1504 having 5μm-thickness and n-type 4H-$Al_{0.25}Ga_{0.75}N$ layer 1505 having 30nm-thickness with carrier concentration of $2 \times 10^{18}\,cm^{-3}$ are grown by MOCVD.

A dry etching process selectively etches the area to be isolated around the channel.

Then, Ti/Al n-type ohmic contact as a source electrode **1506** and p-type ohmic contact as a drain electrode **1507**, and Pd-Si gate electrode **1508** is formed as a source, a drain and a gate of the field effect transistor (FET) as shown in Figure 15. The fabricated FET is easy to be designed without any built-in electric field, which might lead to the enhanced electron mobility with lower series resistance.

The detailed structural parameters of the field effect transistor are summarized in Table 6. Table 6 discloses the thickness and carrier concentration each layers in one example. The uniformly doped n-type 4H-$Al_{0.25}Ga_{0.75}N$ layer **1505** may be a d-doped layer with higher carrier concentration with atomic level thickness.

Although the above five embodiments are disclosed for III-V nitrides on 4H-SiC substrate, the substrate is not limited to SiC and may be, for example, ZnO. The substrate with 4H-polytype such as 4H-SiC and 4H-ZnO is useful for each embodiment. In addition, the III-V nitride layers may be chosen from any composition of $B_{1-x-y-z}In_xAl_yGa_zN$ ($0 \leq x \leq 1$, $0 \leq y \leq 1$, $0 \leq z \leq 1$) alloy. The used (11-20) substrate may be inclined less than 10 degree from the main face towards either <0001> or <1-100> direction.

Having fully described a preferred embodiment of the invention and various alternatives, those skilled in the art will recognize, given the teachings herein, that numerous alternatives and equivalents exist which do not depart from the invention. It is therefore intended that the invention not be limited by the foregoing description, but only by the appended claims.